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Performance Analysis of GTS Allocation in IEEE 802.15.4 Using Omnet++ Simulator

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Abstract: The IEEE 802.15.4 protocol has the ability to support Low Rate Wireless Personal Area Networks (WPANs) with very low power consumption time-sensitive due to the Guaranteed Time Slot (GTS) medium access control mechanism. In this paper, we have analyzed the GTS allocation mechanism used in IEEE 802.15.4 networks. Specifically, we have used Omnet++ simulator to study the impact of varying the time slots allocated for GTS such that a better performance can be guaranteed.

Key words: Wireless Network · IEEE 802.15.4 · Zigbee · SuperFrame · GTS and Omnet++

INTRODUCTION

Wireless Personal Area Network (WPAN) is a wireless network centered around user workspace that typically extends up to 10m in all directions [1]. The focus of WPANs is low-cost, low power, short range and very small size. The IEEE 802.15 working group is formed to create WPAN standard [2]. This group has defined three classes of WPANs that are differentiated by data rate, battery drain and Quality of Service(QoS). These classes are:

- IEEE 802.15.3: The IEEE 802.15.3 is designed for high data rate WPAN and suitable for multi-media applications that require very high QoS [3].
- IEEE 802.15.1/Bluetooth: The 802.15.1 is designed for medium rate WPANs for handling a variety of tasks ranging from cell phones to PDA communications and provides QoS suitable for voice communications [4].
- IEEE 802.15.4: IEEE 802.15.4 is designed for low rate WPANs and it is intended to serve a set of industrial, residential and medical applications with very low power consumption [5].

The IEEE 802.15.4 has many features that are not considered by IEEE 802.15.1 and IEEE 802.15.3 with relaxed needs for data rate and QoS. The low data rate enables the IEEE 802.15.4 to consume very little power. In year 2000, Zigbee and IEEE 802 work group combined efforts to address the need for low cost and low power consumption [6]. ZigBee technology is a low data rate, low power consumption, low cost and wireless networking protocol targeted towards automation and remote control applications. Zigbee has been considered as an alternative for WPAN.

The IEEE 802.15.4 has defined two medium-access modes: Non Beacon-enabled mode and Beacon-enabled mode. In a beacon-enabled network with superframes, a Slotted Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA) mechanism is used. In networks without beacons, unslotted or standard CSMA-CA is used. We focus in this paper on the IEEE 802.15.4 beacon-enabled mode and the details for the non beacon-enabled mode can be found in [5].

To support time-critical data transfers generated by repetitive low-latency applications, the IEEE 802.15.4 can operate in an optional superframe mode. A dedicated network coordinator, called the PAN coordinator, transmits superframe beacons in predetermined intervals. The intervals vary in length from 15ms to as long as 245s. The duration between two beacons is divided into 16 equal time slots independent of the duration of the superframe. A device can transmit at any time during a slot, but must complete its transaction before the next superframe beacon. The channel access in the time slots is contention-based; however, the PAN coordinator is responsible for providing time slots to a single device requiring dedicated bandwidth or low-latency transmissions. These assigned time slots are called Guaranteed Time Slots (GTS).

Many papers have been published studying the efficiency of GTS allocation scheme. The authors of [7] studied the IEEE 802.15.4 standard over ubiquitous

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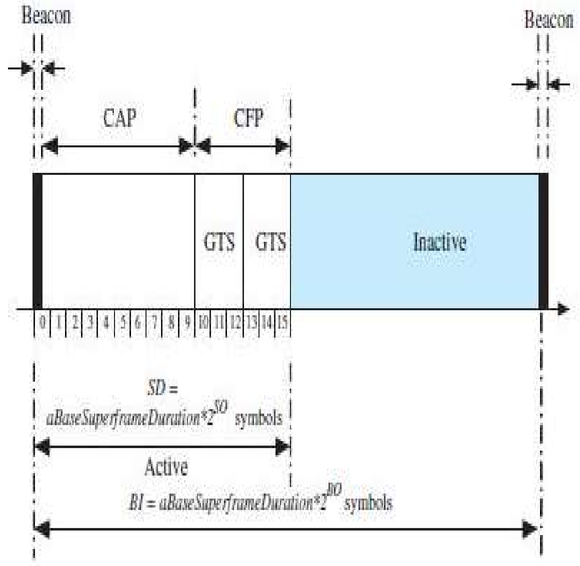

Fig. 1: Superframe structure in IEEE 802.15.4

networks. In [8], the authors worked on the energy-cost analysis of IEEE 802.15.4 beacon-enabled and non beacon-enabled transmission modes. A performance analysis of IEEE 802.15.4-based Body Area Networks (BANs) for medical sensors was presented [9]. The system throughput and the probability distribution of access delay are derived for a beacon-enabled WPAN [10].

This paper illustrates how Zigbee performs when its Guaranteed Time Slot (GTS) functionality is turned on or off and also when we are having a wireless channel that exhibits path loss variation vs. one that it does not. For all of these scenarios, we will vary the packet rate of the sending nodes. Because the PAN coordinator may allocate up to seven of GTS slots, we experimented with various number of GTS slots: 1, 3, 5 and 7 slots. We used Omnet++ simulator [15] in addition to Castalia [17] simulation model to study the impact of varying the time slots allocated for GTS such that a better performance can be guaranteed, concerning maximizing the throughput (more packets are received). Additionally, we observed the application level latency and we found that with three slots allocated for GTSs more packets are still received for a fixed frame length.

The rest of this paper is organized as follows: Section two describes the superframe structure. Section three presents the research methodology. In Section four, our simulation results are presented after conducting a series of experiments. Section five is the conclusion.

The Superframe Structure: A superframe begins with a beacon issued by a PAN coordinator. The superframe can have an active and an inactive portion. Figure 1 shows a superframe structure adopted by the IEEE 802.15.4 beacon-enabled mode [5]. During the inactive portion, the coordinator shall not interact with its PAN and may enter a low-power mode. The active portion consists of Contention Access Period (CAP) and Contention Free Period (CFP). Any device wishing to communicate during the CAP shall compete with other devices using a slotted CSMA/CA mechanism. On the other hand, the CFP contains Guaranteed Time Slots (GTS). The GTS always appears at the end of the active superframe starting at a slot boundary immediately following the CAP.

A GTS shall be used only for communication between the PAN coordinator and a device. The PAN coordinator may allocate up to seven of these GTSs and a GTS can occupy more than one slot period. A single GTS can extend over one or more superframe slots. The duration of different portions of the superframe are described by the values of *macBeaconOrder (BO)* and *mac SuperFrameOrder (BI)*. *macBeaconOrder* describes the interval at which the coordinator shall transmit its beacon frames. $BI = 2^{BO} x$ *aBaseSuperFrameDuration*) and the parameter *macSuperFrameOrder*(*SO*) decides the length of active period ($SD = 2^{SO}$ *x aBaseSuperFrameDuration*) in a superframe, $0 \leq SO \leq 14$. If $SO \leq 15$, the superframe should not remain active after the beacon.

Figure 1 shows that the beacon is transmitted at the beginning of slot 0 without using CSMA. The CAP starts immediately after the beacon. The CAP shall be at least *aMinCAPLength* symbols unless additional space is needed to temporarily accommodate the increase in the beacon frame length to perform GTS maintenance. All frames shall use slotted CSMA-CA to access the channel. However, acknowledgement frames or any data frame that immediately follows the acknowledgement of a data request command that are transmitted in the CAP do not use slotted CSMA-CA. One IFS period is needed for a transmission in the CAP before the end of the CAP. Otherwise, it defers its transmission until the CAP of the following superframe. IFS time is the amount of time necessary to process the received packet by the PHY.

The CFP, if present, shall start on a slot boundary immediately following the CAP and extends to the end of the active portion of the superframe. The length of the CFP is determined by the total length of all of the combined GTS. No transmissions within the CFP shall use a CSMA-CA mechanism. A device transmitting in the CFP shall ensure that its transmissions are complete in one IFS period before the end of its GTS. Transmitted frames shall be followed by an IFS period. The length of IFS depends on the size of the frame that has just been transmitted.

MATERIALS AND METHODS

In order to study the impact of varying the time slots allocated for GTS such that a better performance can be guaranteed, a simulation tool was required. There were several simulation tools that could have been used. The most well-known tools are Global Mobile Information Systems Information Library (GloMoSim) [11] and [12], Optimised Network Engineering Tools (OPNET) [13], Network Simulator (NS-2) [14] and Omnet++ [15]. Omnet++ can support a large number of network components such as different applications, protocols and traffic models.

Objective Modular Network Test-bed in C++ (Omnet++) is a public-source, component-based and modular simulation framework. It is mostly applied to the domain of network simulation and other distributed systems. The Omnet++ model is composed of hierarchically nested modules. The top-level module is called the Network Module. This module contains one or more sub-modules each of which could contain other sub-modules. Various Internet protocol model have been developed on the top of Omnet++ such as the Omnet++ Mobility Framework [16] and Castalia [17].

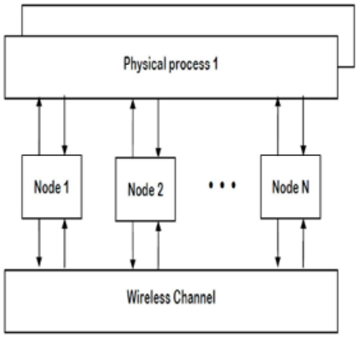

Fig. 2: The modules and their connections in Castalia [17]

Castalia can be used to test distributed algorithms and/or protocols in realistic wireless channel and radio models. It can also be used to evaluate different platform characteristics for specific applications, since it is highly parametric and can simulate a wide range of platforms. Castalia's basic module structure is shown in Figure 2.

The nodes in Castalia are not connected with each other, but they are connected through the wireless channel [17]. The wireless channel is responsible for delivering for example a packet from one node to another. The nodes are also linked through the physical processes that they monitor. The nodes sample the physical process in space and time to get their sensor readings.

Figure 3 shows the internal structure of the node in Castalia. The figure has two types of arrows: 1) solid arrows signify message passing and 2) dashed arrows signify simple function calling. For example, the modules call the resource manager to signal that energy has been consumed.

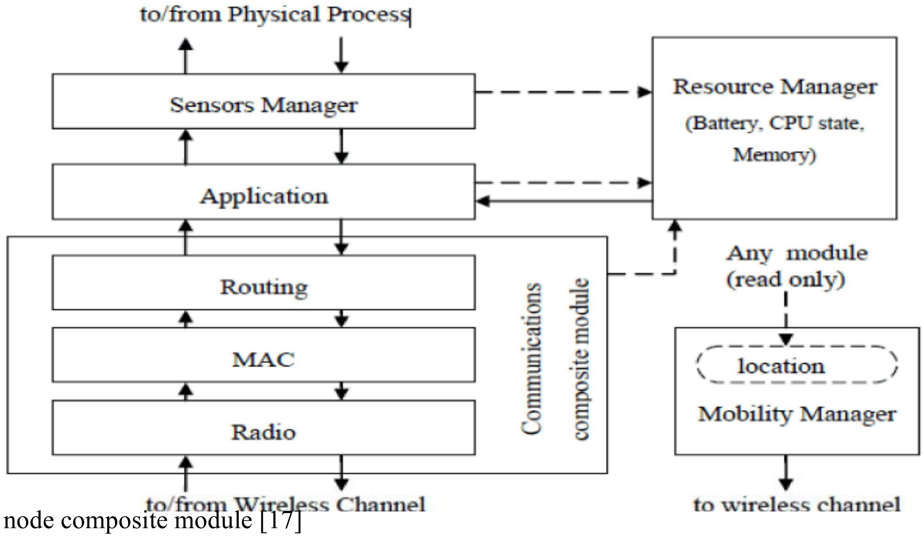

Fig. 3: The node composite module [17]

```
sim-time-limit = 51s  # 50 secs of data + 1 sec of MAC setup

SN.numNodes = 6


SN.node[*].ApplicationName = "ThroughputTest"

SN.node[0].Application.latencyHistogramMax = 600

SN.node[0].Application.latencyHistogramBuckets = 30


SN.node[*].Communication.Radio.TxOutputPower = "-15dBm"

SN.node[*].ApplicationName = "ThroughputTest"

[Config ZigBeeMAC]
SN.node[*].Communication.MACProtocolName = "Mac802154"
SN.node[0].Communication.MAC.isPANCoordinator = true
SN.node[*].Communication.MAC.phyDataRate = 1024
SN.node[*].Communication.MAC.phyBitsPerSymbol = 2

[Config GTSon]
SN.node[*].Communication.MAC.requestGTS = 3

[Config GTSoff]
SN.node[*].Communication.MAC.requestGTS = 0

[Config PathLoss]
SN.wirelessChannel.pathLossFile = "pathLoss.txt"

[Config noPathLoss]
SN.wirelessChannel.temporalModelParametersFile = ""

[Config allNodesVaryRate]
SN.node[*].Application.packet_rate =
${rate=14,16,18,20,22,24,26,28,30}
 [Config setPower]
SN.node[*].Communication.Radio.TxOutputPower = "-15dBm"

[Config allNodesVaryPower]
SN.node[*].Communication.Radio.TxOutputPower = ${power="-
10dBm","-12dBm","-15dBm","-20dBm"}
```

Fig. 4: The configuration file *omnetpp.ini*

The application module is always modified by the user by creating a new module to implement a new algorithm such as MAC and Routing modules, as well as the Mobility Manager module.

A simulation model was built by using both Omnet++ and Castalia to study the impact of varying the time slots allocated for GTS. A configuration file named *omnetpp.ini* was built which contains values of parameters used to test the performance of IEEE 802.15.4 protocol (Figure 4). This file contains mainly the followings:

- The name SN stands for Sensor Network. The number of nodes in our simulation is set to six.
- Node 0 is set to be the PAN coordinator.
- The time slots associated for GTS is associated through *Communication. MAC. requestGTS.*
- The number of packets sent to the source node is specified through *Application.packet_rate*
- The application level latency set to the value of 600ms. *Application.latencyHistogramMax*
- The average path losses between node 0 and the remaining nodes is stored *pathLossFile = "pathLoss.txt".*
- The transmitted power between the PAN node and the other nodes is set by: *Communication.Radio.TxOutputPower*

RESULTS AND DISCUSSION

In our simulation scenarios, the length of the superframe was 16 slots. Therefore, if each of the five nodes is requesting and getting for example 3 slots for each GTS, thus 15 slots in total are devoted to GTS. The remaining slot is always the first slot after the beacon and is using a contention based scheme. When GTS is off then all 16 slots are using contention-based access.

In our simulation, node zero only receives packets and it receives them from multiple nodes, this is what the "per node" means in the figures shown in appendix A. Each node in our simulation is sending certain number of packets per second for duration of 50 seconds. Thus, node zero should receive 1500 packets per node for the 30packets/sec/node case if we have perfect reception. We also run every scenario with 5 different seed sets. The results were obtained as:

- The number of time slots allocated for GTS are: 1, 3, 5 and 7 slots.
- Temporal channel (path loss) exists.
- No temporal channel (no path loss) exists.

The figures in appendix A (Figure 5.a, 5.b, 5.c and 5.d) represents the average number of packets received by node 0 for various number of GTS slots: a) one slot, b) three slots, c)five slots and d)seven slots.

Figure 5.a shows that allocating one slot of GTS exhibits similar performance when the GTS is turned off until the number of packets has reached the value of 26. Then, the number of packets started to decrease despite the presence of GTS. Additionally, Tables 1 and 2 list the number of packets after sending 14 and 30 packets respectively. It is obvious that allocating one slot of GTS a less performance has been achieved.

Figure 5.b shows the number of packets after allocating three slots of GTSs, GTSoff_noPathLoss and GTSon_PathLoss exhibit the same characteristics. This shows the enhancements that the GTS has made on the total number of packets received. Notice that with GTSon_noPathLoss a maximum number of packets received per node. However, with GTSoff_ PathLoss a minimum number of packets received per node is achieved. The protocol performs better when the GTS is turned on when allocating three slots of GTSs. The total number of packets received by the source node after sending 30 packets per second was 1459 packets which is the maximum value achieved and much higher when the GTS is off (Table 2). Figure 5.b also shows that the performance (packets received) is better when the channel has no path loss. Again this is to be expected as the temporal variation introduces some deep fades that break the connectivity between the sender nodes and node 0, whereas with the no temporal path loss variation the links are kept in a relatively good state in our simulation.

As the time slots allocated for GTS became of values 5 and 7, the performance has degraded. Figures 5.c and 5.d show that the number of packets received per node has decreased significantly (Table 1 and Table 2). Our simulation results show that although the PAN coordinator may allocate up to seven slots of GTSs, GTS is efficiently using the wireless medium when allocating three slots of GTSs.

We measured the application level latency as we varied the number of slots allocated for GTS. The length of MAC frame was set to 120 ms. We measured the number of packets for a duration of 600ms. The results in appendix B (Figures 6.a, 6.b, 6.c, 6.d and 7) represent the application level latency for various values of GTS. The results in appendix B show no_pathLoss is performing better than pathLoss as expected. The results also show that most of the packets are received under 100msecs latency, which means that they are transmitted in the first MAC frame after their creation.

Table 1: Number of packets received after sending 14 packets/sec/node (the total number of packets that should be received is 700 packets for 50 seconds)

Time Slots for GTS	Num. of Packets (No Path Loss)	Num. of Packets (Path Loss)
0 (GTS off)	689	645
1	694	653
3	698	677
5	440	422
7	365	345

Table 2: Number of packets received after sending 30packets/sec/node (the total number that should be received is 1500 packets for 50 seconds)

Time Slots for GTS	Num. of Packets (No Path Loss)	Num. of Packets (Path Loss)
0 (GTS off)	1385	1261
1	1321	1180
3	1459	1365
5	920	889
7	67	650

Figure 6.a and 6.b show that there is a difference regarding the number of packets received whether a wireless channel experience a path loss or not. However, Figures 6.c and 6.d show that the number of packets received has not changed whether a path loss exists or not. Obviously, allocating three slots of GTSs more packets are received for the same period and exhibits better performance.

For the results in Figure 7 (GTSoff), we can see that most of the packets are received under 100msecs latency. Unlike the results shown in figure 6.a and 6.b, a non-negligible portion of packets exists at the [600..inf). Figures 6.a and 6.b show that at the [600..inf) interval, we see a more packets with large delay.

CONCLUSIONS

The IEEE 802.15.4 defines two medium-access modes: Non beacon-enabled mode and Beacon-enabled mode. We focused in this paper on the IEEE 802.15.4 beacon-enabled mode. IEEE 802.15.4 provides a Guaranteed Time Slots (GTS) mechanism to allocate a specific duration within a superframe. We investigated the performance of the GTS mechanism for IEEE 802.15.4 WPANs in the beacon-enabled mode. We used Omnet++ simulator and Castalia simulation model to conduct our experiments. Our simulations results shows that although the PAN coordinator may allocate up to seven slots of GTSs, GTS is efficiently using the wireless medium (more packets are received) when allocating three slots of GTSs. We observed the application level latency and we found that with three slots allocated for GTSs more packets are still received for a fixed frame length.

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Appendix A

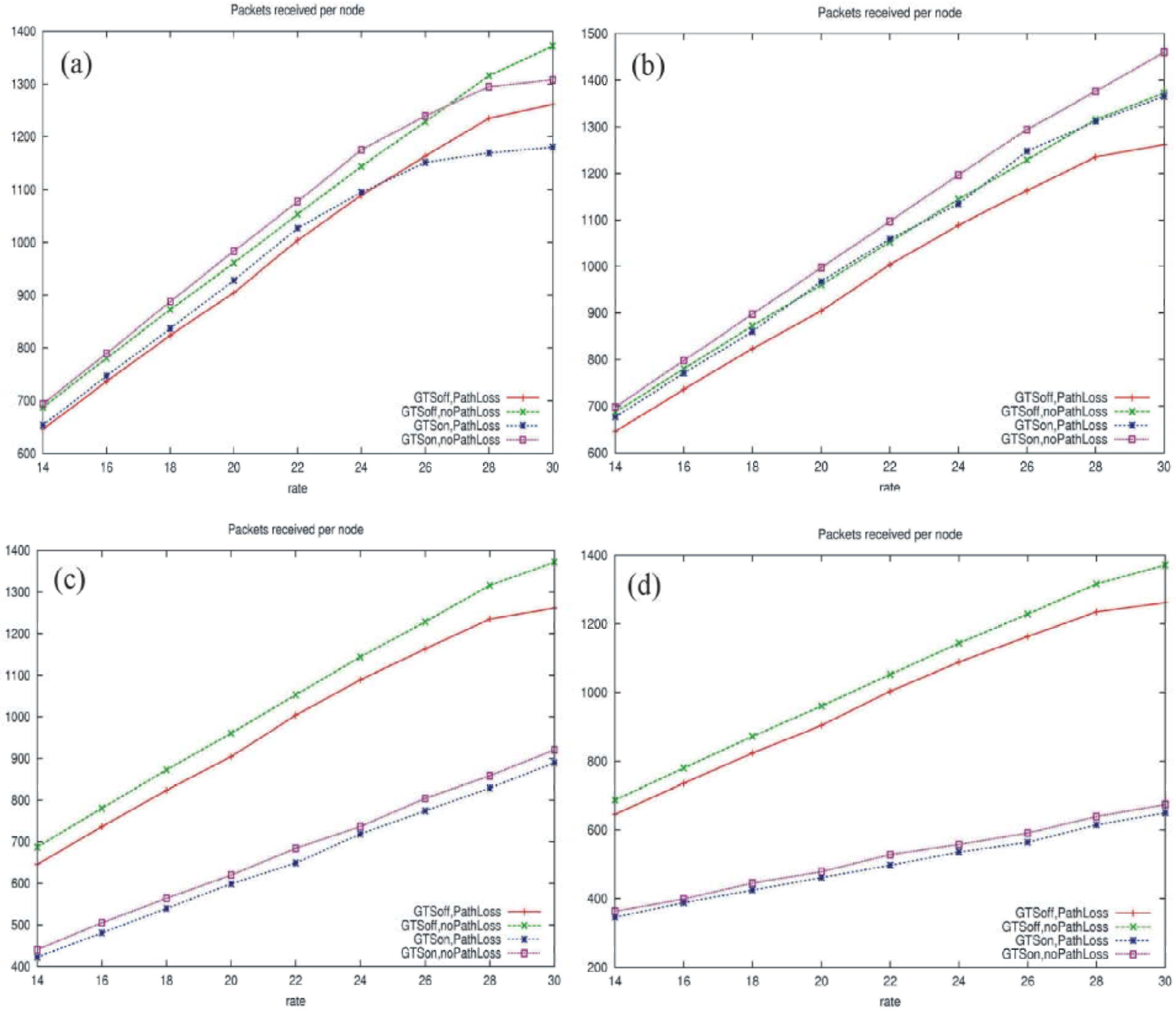

Fig. 5: The average number of packets received by node 0 for various number of GTS slots: a) one slot, b) three slots, c)five slots, and d)seven slots.

Appendix B

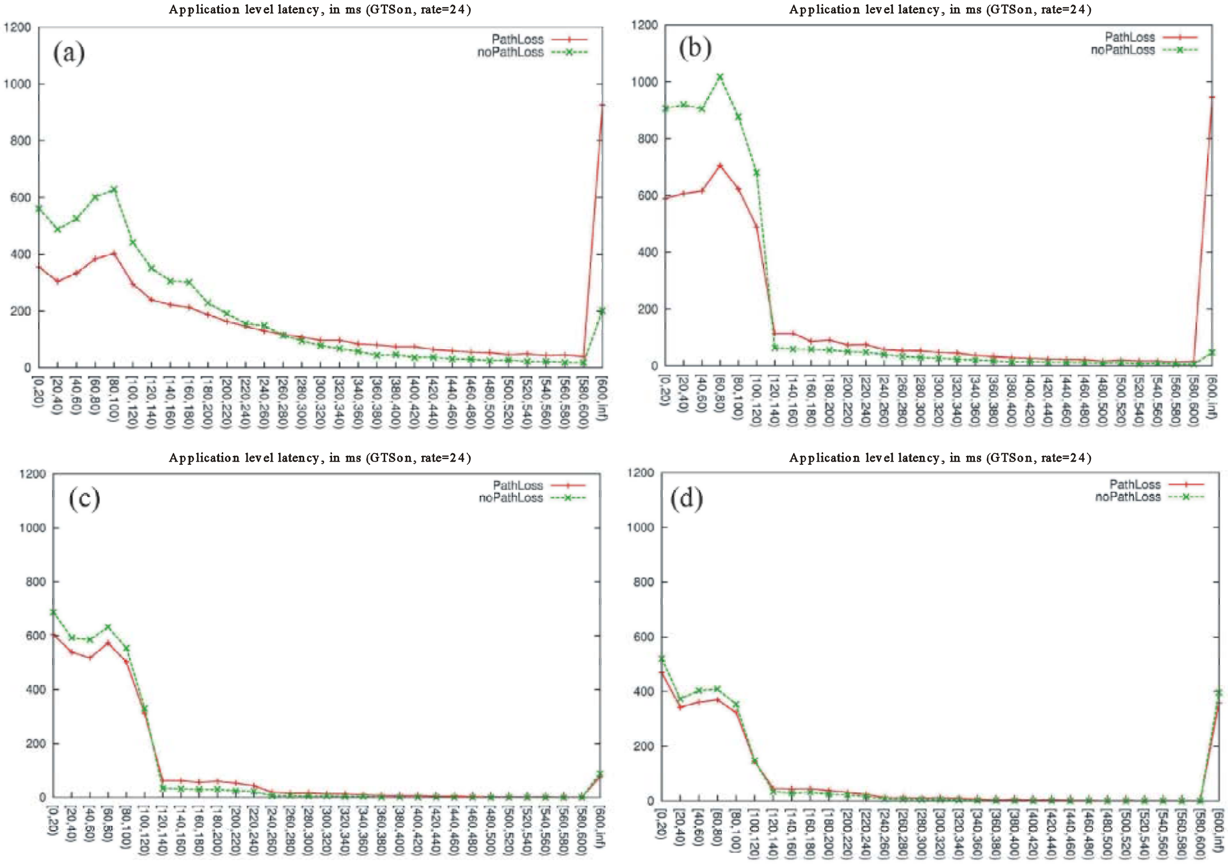

Fig. 6: The application level latency for various number of GTS slots: a) one slot, b) three slots, c) five slots and d) seven slots.

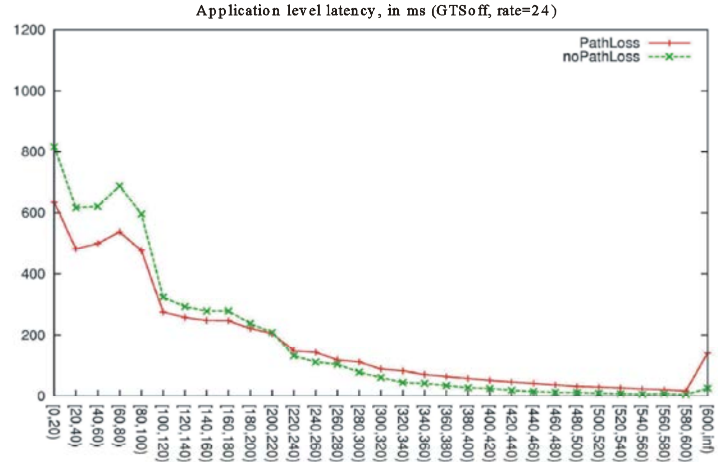

Fig. 7: The application level latency when GTS is off.